

HST imaging of redshift $z > 0.5$ 7C and 3C Quasars

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Abstract. We present preliminary results from HST imaging of radio-loud quasar hosts, covering a $\sim \times 100$ range in radio luminosity but in a narrow redshift range ($0.5 < z < 0.65$). The sample was selected from our new, spectroscopically complete 7C survey and the 3CRR catalogue. Despite the very large radio luminosity range, the host luminosities are only weakly correlated (if at all) with radio power, perhaps reflecting a predominance of purely central engine processes in the formation of radio jets, and hence perhaps also in the radio-loud/-quiet dichotomy at these redshifts. The results also contradict naive expectations from several quasar formation theories, but the host magnitudes support radio-loud Unified Schemes.

1 Introduction

The strong evolution of quasars from redshifts $z = 2$ to $z = 0$ is very well documented but poorly understood. Their evolution may reflect changing merger rates (*e.g.* Carlberg 1990) or may reflect processes in galaxy formation *via* the changing formation efficiency of nuclear black holes (*e.g.* Haehnelt & Rees 1993). Alternatively, Small & Blandford (1992) suggest that the largest galaxies, hosting the brightest quasars, formed first (contrary to “bottom-up” hierarchical structure formation); quasar evolution is then ascribed to a luminosity-dependent transition from continuous to intermittent activity. Physically, this could be interpreted as an initial quasar phase in newly-forming galaxies followed by merger-driven events.

Each of these models has a wide parameter space in which to accommodate strong positive quasar evolution, which reflects the essential lack of a physical understanding. Nevertheless, the various classes of models make widely different predictions for the immediate environments of the active nuclei. For example, in merger-driven quasar evolution one expects tidal features or disturbed morphologies in the host galaxies, possibly more disturbed at higher z ; in models where a quasar stage is common in bottom-up galaxy formation, one expects that quasars of a given luminosity have increasingly smaller host galaxies, with increasing redshift, but in the Small & Blandford (1992) model one predicts an opposite trend.

Host galaxies also provide a useful test of radio-loud unified schemes (*e.g.* Antonucci 1993). If dust shrouded quasars are universal in radiogalaxies, then there

must be identical host galaxy properties in radioquasars and radiogalaxies. However, in making such comparisons one must ensure the quasar and radiogalaxy samples are well-matched in some isotropic quantity, such as hard X-ray luminosity or radio lobe luminosity. Unfortunately, the only large, complete (published) sample of lobe-dominated quasars is from the 3CR catalogue, in which radio luminosity is tightly correlated with redshift. This makes it difficult to address the evolution of any parameter, such as host galaxy luminosity, because of the possibility of radio luminosity dependence. In this paper we present a complete sample which breaks this degeneracy by comparing 3CR quasars with a new coeval, spectroscopically complete sample ~ 100 times fainter in radio luminosity.

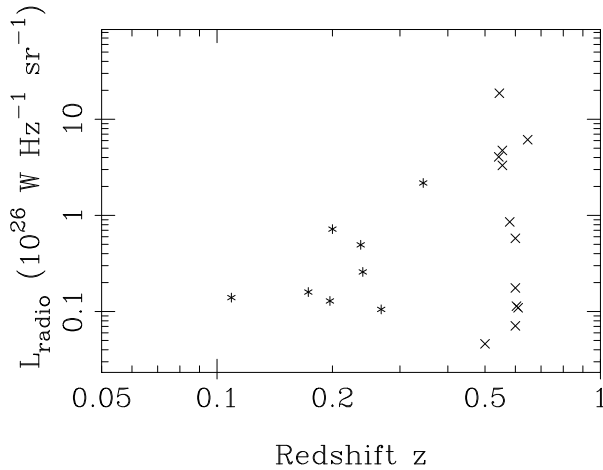


Fig. 1. Radio luminosity-redshift plane for our sample (crosses) and steep-spectrum quasars from Dunlop *et al.* (1993)

2 Data Acquisition and Analysis

2.1 Sample definition

We have recently completed spectroscopic campaign on the INT and NOT of steep-spectrum quasars (SSQs) from the 151MHz 7C catalogue (McGilchrist *et al.* 1990), which has a limiting flux density of $S_{151} = 0.1\text{Jy}$. This sample is ideal for comparisons with coeval quasars from the 178MHz 3CR catalogue (Laing, Riley & Longair 1983), since the high flux limit of $S_{178} = 10\text{Jy}$ in the latter gives a wide dispersion in radio luminosity at any epoch. VLA snapshots of 7C obtained by us confirmed that the 3C and 7C SSQs are from the same parent population; both samples consist of FR II sources with cores. As we will show below, this allows us to decouple luminosity dependence from evolution.

We were awarded twelve orbits to image a subsample of 3C and 7C SSQs with the HST WFPC2. Our sample selection was driven by several competing requirements:

- spectroscopic completeness;
- freedom (as far as possible) from beaming and gravitational lensing biases;
- a narrow redshift interval, to counter any potential differential evolution;
- a choice of filter and redshift range avoiding strong emission lines;
- as red a filter as possible to maximise the contrast between the quasar and its host;
- the highest accessible redshifts for reliable detection of host galaxies.

Our choice of SSQs (as opposed to flat-spectrum quasars) ensured our samples were largely free from lensing and beaming since the steep-spectrum radio fluxes are dominated by extended, optically thin synchrotron emission.

Based on crude models of PSF-subtracted frames, we estimated that SSQ hosts should be detectable at $z \lesssim 0.6$ if Unified Scheme predictions hold, *i.e.* that the host galaxies are giant ellipticals. Our targets were therefore confined to the interval $0.5 < z < 0.65$, to be imaged in the F675W filter which successfully avoids the [OII] 3727Å, [OIII] 5007Å and H β emission lines. The complete 3CR and 7C samples contain 12 steep-spectrum quasars in this redshift interval. The very wide range in radio luminosity of our sample is demonstrated by the vertical dispersion in figure 1.

Also plotted on figure 1 are steep-spectrum quasars from the sample of Dunlop *et al.* (1993). Using samples such as these we can therefore make comparisons between well-matched quasars between epochs (*i.e.*, in a horizontal slice of figure 1), which for the first time are free of the luminosity dependence which mars studies of 3C alone.

Moreover, even at the median redshift of our sample ($z \sim 0.6$) the quasar number density is already around an order of magnitude larger than the present (*e.g.* Dunlop & Peacock 1990). Our sample is therefore (in principle at least) capable of probing any environmental causes of quasar evolution.

Fortuitously, two of the 3CR targets (3C334 and 3C275.1) also have ground based detections of giant host galaxies, which was not realised when defining the survey selection criteria. These detections provide important corroborations of our photometry and quasar subtraction technique. It is perhaps significant that these large host galaxies, among the largest for any quasars, are at the highest possible redshifts for optical ground-based detections.

2.2 Data acquisition

For the majority of the targets we broke our observations of each quasar (one orbit per quasar) into four separate exposures. Two of the four exposures were offset by 5.5 pixels in both directions, to assist with the positioning of the quasar in the central pixel (recall that the Planetary Camera slightly undersamples). Although this strategy might be expected to present problems with the cosmic

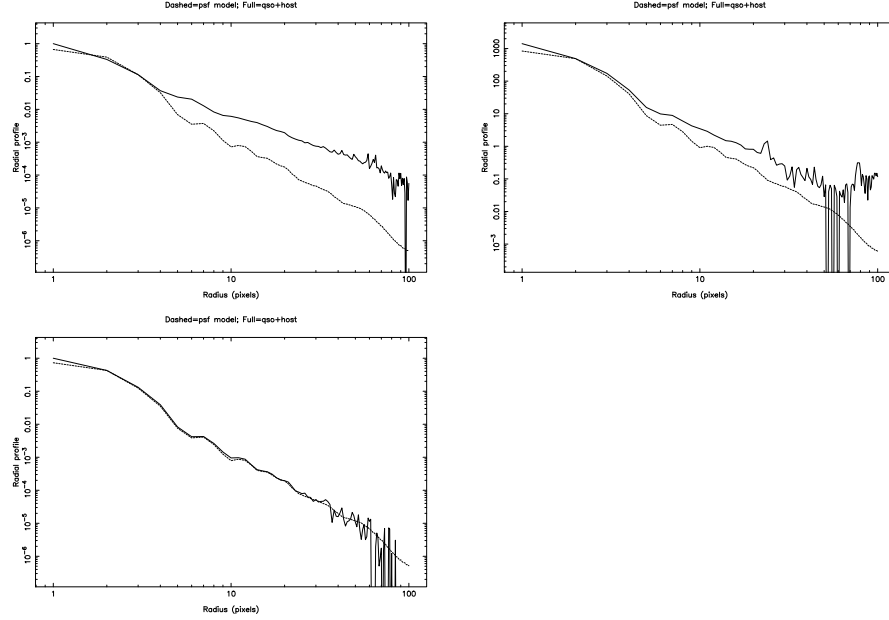


Fig. 2. Radial profiles for 3c275.1 (top left), the brightest host in our sample, and for a more typical target (7C2886, top right). The uprise at large radii in the latter is due to a companion galaxy. In both cases the Tiny Tim PSF is also plotted, normalised to the first unsaturated pixel. Also shown is the empirical PSF compared to the Tiny Tim model (bottom).

ray subtraction, we found that the cosmic rays could be identified and removed adequately using the CRREJ algorithm in the IRAF IMCOMBINE task, despite having only two frames per position.

Sky subtraction was achieved by selecting regions of the planetary camera frame free of bright objects, and constructing a histogram of pixel values (choosing bin sizes and widths to minimise the digitisation effects); the sky levels were then estimated by fitting Gaussians to these histograms.

2.3 Point spread functions

Since the Planetary Camera undersamples the point spread function, the pixel to pixel variations may depend strongly on the position of the quasar within the central pixel. We therefore expected that our QSO subtraction would be improved by determining this position *via* a cross correlation of the quasar frame with a model oversampled point spread function from Tiny Tim version 4.0 (Kirst 1995). The oversampled model would need to be rebinned to the cruder Planetary Camera pixel scale at each proposed centre, and a least squares solution found for the central position. One small complication in this cross correlation is the existence of a non-negligible pixel to pixel scattering function. The resampled point spread functions must therefore be convolved with the

appropriate kernel from Kirst (1995) before comparisons are made with the data frame.

To complement the Tiny Tim models, we also constructed an empirical point spread function from our standard star observations, masking out saturated pixels before coaddition. An undersampled empirical point spread function for this filter was unfortunately not available.

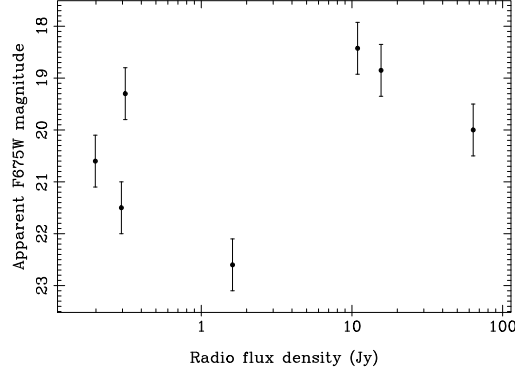


Fig. 3. Apparent F675W magnitudes of the hosts measured to date. Note the lack of, or only weak presence of, a correlation with radio flux. The F675W magnitude system is about half a magnitude fainter than Cousins R.

3 Results

3.1 Robustness of host magnitudes

We attempted QSO subtractions using PSFs obtained by three methods: an arbitrarily centred model PSF, the empirical PSF discussed above, and a PSF centred on the QSO by cross correlation above with saturated pixels masked out. For the first two, we determined the PSF normalisation from the radial profiles, using the first unsaturated pixel. In the case of the cross-correlation method, these normalisations were in excellent agreement with those obtained independently from the cross-correlation itself. Although specific features such as diffraction spikes are better reproduced, the total magnitudes were (reassuringly) found to be insensitive to the PSF centering. We also attempted normalising to the diffraction spikes, but the results were much less satisfactory. Nevertheless, the host magnitudes were not found to be sensitive to the masking -or not- of the diffraction spikes. The results for the quasars examined to date are shown in figures 2 and 3. The previous ground-based detections of host galaxies in 3C275.1 and 3C334 are well reproduced by our algorithms. From the dispersion between the different methods, we estimate an error of $\sim \pm 0.2$ in our host galaxy magnitudes.

We used azimuthal averaging to reach fainter flux levels, as used by several other authors (figure 2). We might hope to obtain a morphological classification from fits to the radial profiles (*e.g.* exponential disk, de Vaucouleurs profile); this involves fitting to the curvature of the PSF-subtracted profile, which is not as well constrained as the total host magnitude. Furthermore, the reasonable inclusion of a bulge component to a disk model was found to introduce too many free parameters. This will be discussed in more detail in Serjeant *et al.* (1997), which also compares one- and two-dimensional fits to our data.

4 Discussion and Conclusions

Remarkably, the host magnitudes are only weakly dependent -if at all- on radio luminosity, despite the very wide dispersion in radio luminosity ($\sim \times 100$; see figure 3). This may reflect a predominance of purely central engine processes in the formation of radio jets, and hence perhaps also in the radio-loud/-quiet dichotomy at these redshifts. If so, we predict that the radio-quiet and radio-loud hosts should be similar by redshifts $z \simeq 0.6$.

We can compare figure 3 with the R magnitudes of radiogalaxies in our redshift range from the samples of Lacy *et al.* 1993 and Eales 1985. Both the radiogalaxies from these studies and our SSQ samples were selected in an orientation-independent manner; these radiogalaxies have $18.5 < R < 21.0$ which is clearly well reproduced by our data, supporting radio-loud Unified Schemes.

The results also contradict naive expectations from several quasar formation theories. In both the Haehnelt & Rees (1994) model (if applicable at this z) and the Small & Blandford (1992) model strong trends of host properties are expected with redshift (see introduction), whereas giant ellipticals appear to host most radio-loud AGN at $0.2 < z < 0.7$ (*e.g.* Taylor *et al.* 1996).

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